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SIMPLE ANALYSIS OF LIGHT ION BEAM LOSSES IN DEUTERIUM PLASMA CH--ETC(U)
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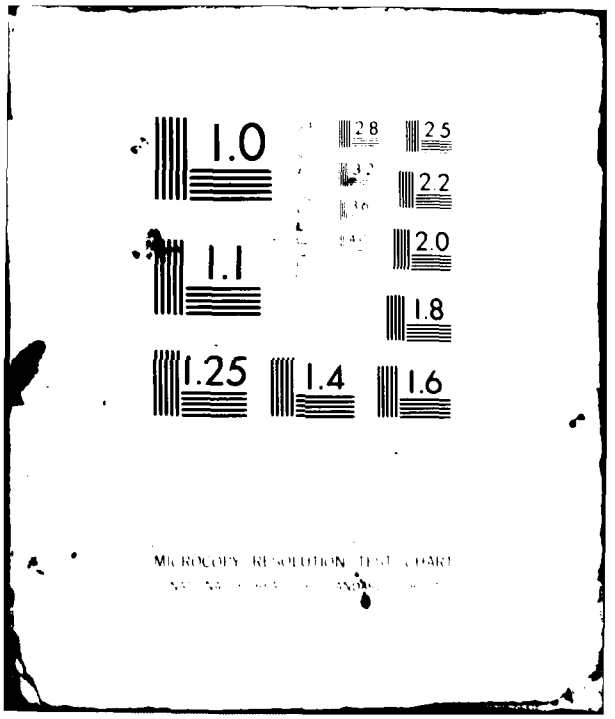
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REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER: NRL Memorandum Report 4640	2. GOVT ACCESSION NO.: AD-A108 287
	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): SIMPLE ANALYSIS OF LIGHT ION BEAM LOSSES IN DEUTERIUM PLASMA CHANNELS	5. TYPE OF REPORT & PERIOD COVERED: Interim report on a continuing NRL problem
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): D. G. Colombant and S. A. Goldstein*	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Naval Research Laboratory, Washington, DC 20375	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: JO 47-0879-0-1; Sponsor Assignment No. DE-A108-79DP40092
11. CONTROLLING OFFICE NAME AND ADDRESS: U.S. Department of Energy, Washington, DC 20545	12. REPORT DATE: November 16, 1981
	13. NUMBER OF PAGES: 29
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

*Jaycor Inc., Alexandria, VA

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Light ion beam propagation
Beam transport efficiency
Beam channel response

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Simple analysis of both ion beam energy losses and beam current density reduction is presented for deuterium plasma channels. It is found that whereas an optimum density may exist for reducing the beam energy losses in the channel, no optimum density can be found to minimize the beam current density reduction. Plasma channel radius effects are then examined. It is found that the total ion beam energy loss is not strongly dependent on the initial channel radius. We conclude that final focusing elements in conjunction with channels initially at rest allow

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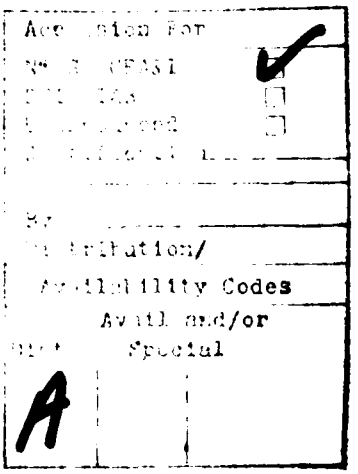
20. ABSTRACT (Continued)

for multiterawatt beams to be transported efficiently to 1 cm^2 targets while the channel cross-section can be larger.

CONTENTS



SIMPLE ANALYSIS OF LIGHT ION BEAM LOSSES IN DEUTERIUM PLASMA CHANNELS

I. Introduction

In a previous paper,[1] the magnetohydrodynamic response of plasma channels to propagating light ion beams has been investigated. The half a centimeter radius channels were assumed to be deuterium at around 10^{-5} g/cm with 50 nsec pulses of .4-1MA/cm^2, 3-5 MeV proton beams injected into them. Basic phenomena like beam collisional energy losses, heating of the channel, expansion of the channel due to beam pressure and the resulting reduction in confinement were shown to take place over the duration of the beam pulse. While a window on the plasma density was given, no optimum for propagation was defined. In this paper, we present a simple analysis to optimize power density transport of the ion beam through the channel and show when such an optimization process is possible. In particular, we concentrate on the energy delivery at the tail of the beam because both voltage and current are highest at that time (as a result of bunching requirements.) We consider separately the ion beam total energy losses and the current density reductions in the plasma channel. We look successively into these two areas and combining them together, we look into the optimization of the power density after transport in the channel.

This analysis applies primarily to deuterium plasma channels where radiation losses are assumed to be negligible. If the beam pulse length were short enough or the plasma channel density high enough, negligible motion would be induced into the channel by the beam over the pulse duration of the beam pulse. However for very short beam pulse length, not enough energy would be available in the beam. For high channel density, beam energy losses would be too large and therefore one must decrease the channel density and allow channel motion on the time scale of the beam pulse duration. This motion then changes the channel confinement characteristics.

Manuscript submitted August 25, 1981

Two kinds of effects are thus to be considered: energy losses and beam current density reductions. The beam energy losses are due to decelerating electric fields in addition to the binary collisional energy losses and beam current density reductions are related to the plasma channel radial expansion. These two different kinds of effects will be treated separately. Combined together, they lead to a new concept of overall transport efficiency which we define as

$$\eta_{tr} = \eta_\epsilon \eta_J = \frac{\epsilon_{out}}{\epsilon_{in}} \frac{J_{out}}{J_{in}} \tag{1}$$

where J refers to beam current density, ϵ to beam energy (MeV/proton), "out" to values at the end of the channel and "in" at the channel entrance (beam injection values).

A brief examination of the channel parameters shows that the plasma density in the channel and the plasma channel radius just prior to beam injection are some of the easiest to change. Parameters which characterize channels are chemical composition, magnitude of the current I_{ch} which flows through them, current density profile $j_{ch}(r)$, radius r_{ch}, mass density distribution $\rho(r)$ and also radial velocity distribution in the channel $v(r)$ prior to beam injection. Recently, imploding channels[2] have also been proposed as a medium for transporting ion beams and they are presently under investigation. In the present paper, we confine ourselves to the following choices: Deuterium gas constitutes the background channel material in order to be able to neglect radiation losses. The channel discharge current follows from the beam characteristics only and is given by $I_{ch}(A) \approx .5\ 10^{-3} \theta_m^2 V_0$ (cm/sec) where θ_m is the maximum beam injection angle and V_0 the ion beam initial velocity. The current density is assumed to be uniform up to the channel radius. In a light ion beam transport scheme,[3,4] the beam is first focused then transported at a radius comparable to the target radius before hitting the target. Different possibilities for the relationship between the channel and the target radii are described later in this paper. The channel configuration has been assumed to be a z-discharge initially at rest ($v_r = 0$ at $t = 0$). This has been shown to be experimentally and theoretically MHD stable on the channel formation time of a few μsec.[5,6] The mass density radial distribution in the channel prior to beam injection is assumed to be independent of the radius. Its magnitude can be varied over several orders of magnitude up to a limit ρ_a when energy losses become too large. This value is given by

$$\rho_a SL = \alpha\epsilon \tag{2}$$

where S is the binary collisional stopping power, L is the length over which the beam is to be transported, and α is the fraction of the initial beam energy which is allowed to be lost during transport. For fully ionized deuterium, $S \approx 10^3/\epsilon$ MeV/g/cm^2 where ϵ is the proton energy in MeV. The transport length L derived from bunching considerations is

$$L\left(\frac{1}{v_0} - \frac{1}{v_\tau}\right) = \tau \tag{3}$$

where v_0 and v_τ are respectively the ion velocities at the head and the tail of the beam and τ is the beam pulse duration, all these quantities being defined at the channel entrance. For $v_\tau = 2v_0$ (energy ramp increasing to twice its initial value), $L(\text{cm}) = 3.3\ 10^9\ \epsilon\tau$ (sec). Combining Eqs. (2) and (3), we find a value for ρ_a equal to

$$\rho_a = \frac{\alpha\ 3.10^{-13}\ \epsilon^{3/2}}{\tau}. \tag{4}$$

For $\epsilon = 5$ MeV, $\tau = 50$ nsec, and $\alpha = 20\%$, $\rho_a = 1.3\ 10^{-5}$ g/cm^3.

A minimum density must also be achieved in the channel in order to ensure charge and current neutralization and also not to excite electrostatic instabilities. If such instabilities are excited, the plasma resistivity becomes much larger than Spitzer resistivity which causes an increase in the net current as well as large electric fields. If these instabilities are not excited, Spitzer resistivity can be assumed and typical diffusion time of the net current are of the order of a few μ sec. Thus during a typical beam pulse, a net current of the order of 1% of the beam current will be added to the channel as was observed in numerical solutions.[1] To avoid electrostatic instabilities,[7] $n_p \gtrsim 5 \times 10^{17}$ for the above parameters. This minimum density is about an order of magnitude smaller than ρ_a given in the example above, hence no plasma instabilities occur if more than a few % fractional energy loss is allowed.

II. Electric Field Generation

At $t < 0$, there is a small electric field in the channel corresponding to I_{ch}. As the beam enters the channel, electric fields from various sources develop. From the generalized Ohm's law, they are

due to channel expansion with velocity v_p which leads to $v_p B/c$ and plasma resistivity. In addition, there is an equivalent electric field due to beam energy collisional deposition.

The electric field terms are all negative with the possible exception of the first one for an imploding channel. The energy losses can be written

$$\frac{dE}{dx} = \left[\frac{v_p B}{c}\right] + \rho S + \eta j_p$$

where the brackets mean average over an ion betatron orbit. The first term goes from 0 at the channel center ($B = 0$, $v = 0$) to a maximum value at the channel boundary where v_p and B usually reach their maximum. For the purpose of the present simple analysis, a mean value is used for this term which is equal to 1/2 of its maximum value. Term by term, the electric field is thus:

a) $\dfrac{<v_p B>}{c}$.

From Ref. 1, we get $v_p \approx \dfrac{t j_b B}{\rho_0 c}$. However, this relation is correct to zeroth order only. If we take into account the fact that the mass density decreases due to expansion, then to first order, the expression for the radial velocity becomes

$$v_p \approx \frac{t j_{b0} B_0}{c\rho_0(1+\chi)} \tag{5}$$

where

$$\chi = \frac{3\ 10^{-2} j_{b0} j_{ch0} t^2}{\rho_0} \tag{6}$$

is the expansion parameter and the 0 subscripts refer to channel and beam conditions at injection. The reduced velocity is due to the fact that the $(j \times B)$ term driving the expansion decreases with radius faster than the mass density (the current density decreases in the same way as the mass density and the B field decreases by a factor $(1 + \chi)$ as will be shown in Sec. III). Now $B_0 = \dfrac{I_{ch}}{5r_0}$, so that

$$\frac{<v_p B>}{c} = \frac{v_p B}{2c} \approx 6.4\ 10^{-11} \frac{j_{b0} j_{ch0} I_{ch0} t}{\rho_0 (1+\chi)^2}. \tag{7}$$

Note that this term is inversely proportional to ρ_0 for small χ and proportional to ρ_0 for large χ. Our simple analysis does not apply to that latter case.

b) ρS.

This term is simply $\frac{\rho_0}{(1+\chi)^2}\frac{10^9}{\epsilon}$ V/cm for protons in deuterium with $T_e \gtrsim$ keV. It is proportional to ρ_0 for small χ and becomes proportional to ρ_0^3 for large values of χ (which correspond to small ρ_0).

c) ηj_p.

Using Spitzer resistivity justified by operating at densities around 10^{18} cm^{-3} to avoid instabilities, this term is proportional to $\frac{Z\ln\Lambda}{T_e^{3/2}} j_b$ where the plasma return current density j_p has been assumed to be equal in magnitude to the beam current density j_b. Due to the small net current ($j_{cn} << j_b$) the most critical quantity to determine in this expression is T_e. Assuming no radiation losses, we know from Ref. 1 that $T_e \approx 3.5\ 10^3 \frac{j_{b0} t}{\epsilon}$ so that for $\chi << 1$,

$$\eta j_b \approx 7.7\ 10^{-8} \frac{\epsilon^{3/2}}{j_{b_0}^{1/2} t^{3/2}(1+\chi)} \text{ V/cm} \tag{8}$$

where t is in sec and j_{b0} in A/cm^2. An order of magnitude estimate shows that this resistive electric field is equal to 40 V/cm for $j_{b_0} = 10^6$ A/cm^2, $t = 50$ nsec and $\epsilon = 3$ MeV. Its dependence on density is very weak for small χ. Collecting all the terms, the total energy losses may then be written as

$$\frac{dE}{dx} = \frac{A}{\rho_0[1+\chi(t)]^2} + \frac{B\rho_0}{[1+\chi(t)]^2} + \frac{C\epsilon^{3/2}}{j_{b_0}^{1/2} t^{3/2}[1+\chi(t)]}. \tag{9}$$

From the first two terms, we see that $\frac{dE}{dx}$ may reach a minimum as a function of ρ_0 for small χ. We find that this minimum is reached for

$$\rho_0 = \left(\frac{1-\chi}{1+3\chi}\right)^2 \left(\frac{A}{B}\right)^{1/2}. \tag{10}$$

Note that $\chi \leqslant 1$ is a necessary condition for a minimum to exist. For small χ, the density corresponding to this minimum is

$$\rho_0 = \left(\frac{A}{B}\right)^{1/2} = \frac{1.4\ 10^{10} t^{1/2} j_{b_0}^{1/2} I_{cn_0} \epsilon^{1/2}}{r_{cn_0}}. \tag{11}$$

This expression physically equates the energy losses due to binary collisions to the energy losses associated with the plasma expansion. Going back to the general case, since we have seen that χ is a function of ρ_0, Eq. (10) is an implicit equation for ρ_0. Eliminating this ρ_0 between Eqs. (7) and (10), a relationship between the various beam parameters when a minimum in the electric field occurs is obtained

$$j_{b_0} t^3 = 2.2\ 10^{-14}\ r_{ch_0}^2 \epsilon \chi^2 \left(\frac{1-\chi}{1+3\chi} \right). \tag{12}$$

This equation shows that when a minimum E field exists, a given fractional expansion χ sets a relationship between the beam pulse duration and the beam current density. A complete solution to Eq. (9) is shown in Figs. 1 and 2. It corresponds to $j_{b_0} = 1$ MA/cm^2, $I_{ch_0} = 50$ kA, $r_{ch_0} = 0.56$ cm, $\epsilon_b = 3$ MeV in Fig. 1 and $\epsilon_b = 5$ MeV in Fig. 2. We find indeed that the minimum in the electric field exists only for small pulse durations. From Eq. (12) it is apparent that $j_{b_0} t^3$ has a maximum as a function of χ which occurs for $\chi = .6$. For longer pulse durations or larger j_{b_0} there will be no minimum in the electric field. This happens for $t \gtrsim 25$ ns in the example of Fig. 1. At the same time that the minimum disappears, the expansion increases and while the beam current density decreases the electric field losses decrease also. For bunched cases, ($j_{b_0} t$ = const), we see from Eq. (12) that a minimum will be reached more easily since now t^2 is smaller. It is important to keep the resistive term in the electric field at shorter pulse durations (unbunched) since in that case, the resistivity can be significant because the beam did not have time to heat up the channel to large temperatures. The expression for the energy efficiency follows directly from Eq. (9). It can be written as

$$\eta_\epsilon = \frac{\epsilon_{out}}{\epsilon_{in}} = \frac{\epsilon_{in} - EL}{\epsilon_{in}} = 1 - \frac{EL}{\epsilon_{in}}.$$

Using typical E-field values of Fig. 1, $E = 1.5$ kV/cm, $L = 3$ m and $\epsilon_b = 3$ MeV, η_ϵ equals 85%.

III. B_θ Field Modifications

At $t < 0$, the B_θ-field configuration is assumed to be that shown in Fig. 3a. It corresponds to a uniform channel current density following the formation of a low temperature channel where the magnetic field had time to diffuse. After beam injection, we assume that the temperature of the channel

has increased due to beam deposition and that the expansion is self-similar (the velocity increases linearly from the center to the edge of the channel). Because of the large conductivity due to channel heating, we assume that the B-field has been convected out with the plasma channel and that the maximum B-field is now reached at $r(1+\chi)$ as shown in Fig. 3b. Its maximum value has decreased from B_0 to $B_0/(1+\chi)$ since the same total current I_{ch} is assumed to flow in the channel. In fact, this assumption keeps the total flux $\int Bdr$ constant and the beam stays confined. We assume that the beam adjusts instantly to new channel conditions and that the change in beam radius follows the change in channel radius. Thus, because of the expansion, the current density is reduced by a factor $(1 + \chi)^2$. This model assumes a free channel expansion and does not take into account the fact that there can be a sharp density jump at the channel boundary, nor that the temperature has remained low in the outer region leading to diffusion of the B-field there.

The current density reduction factor is thus

$$\eta_J = \frac{J_{\text{out}}}{J_{\text{in}}} = \frac{1}{(1+\chi)^2}. \tag{13}$$

In the present form (no ∇p effects on χ), it does not depend on beam energy. It does not show any extremum and leads to low values of η_J ($\leqslant 50\%$) when channel expansion occurs ($\chi \geqslant 0.4$). This current density drop due to channel expansion may be more restrictive than electric field losses as seen in Fig. 4.

We can now combine the energy transport efficiency η_ϵ and η_J in one quantity defined as:

$$\eta_{tr} = \eta_\epsilon \eta_J.$$

This expression can be written in terms of first order quantities again and the analysis is quite lengthy. It can be shown that a maximum for η_{tr} occurs as a function of ρ_0. Physically, it happens because η_ϵ decreases for increasing ρ_0 while η_J increases. An implicit equation for this optimum value of the density is given by

$$\rho_0 = \frac{(1-C')(1+\chi)^2\chi \pm \sqrt{(1-C')^2(1+\chi)^4\chi^2 + A'B'(1+5\chi)(1+3\chi)}}{A'(1+5\chi)}$$

where

$$A' = AL/\epsilon$$
$$B' = BL/\epsilon$$
$$C' = C\epsilon^{1/2}L/(j_{b_0}t)^{1/2}.$$

Figures 5 and 6 show η_{tr} for the same parameters as used in Figs. 1 and 2. We see that the maximum occurs for increasing ρ_0 as the beam pulse duration increases and that this maximum is very broad. The maximum values for η_{tr} depend on the energy of the beam which affects the energy transport efficiency. These calculations have been made for a 3 m long channel — longer channels would reduce the energy efficiency further. For these conditions, we see that it is difficult to achieve an overall η_{tr} greater than 50% for long pulses ($t \geq 40$ nsec). In order to increase the total efficiency, it is necessary to consider transport schemes that have the following options:

a) the channel expansion is limited by means such as surrounding gas blanket or magnetic field.

b) the channel implodes initially.

c) the channel is allowed to expand but is followed by a focusing element.[8]

IV. Effects of Plasma Channel Radius

The previous analysis has been made supposing that the plasma channel radius was 0.56 cm initially (corresponding to an area of 1 cm^2). However, the conclusions just reached suggest the use of a focusing element after the transport plasma channel as one possibility. This solution has very important implications for the whole transport scheme concept. It indicates that a) constraints on the channel radius can be relaxed and transport can be performed at a radius larger than the target radius b) current density reductions can be compensated for by focusing the beam at the end of the channel whereas energy losses cannot. In this section, we look briefly at the influence of channel radius on both energy losses and transport total efficiency. The formulation is the same as that used previously. We just

replace the beam and channel current densities by the beam and channel total current divided by πr_{ch0}^2. The total efficiency can then be written

$$\eta_{tr} = \frac{1}{\left[1+\frac{\alpha}{r_{ch_0}^4}\right]^2} \left\{ 1 - \frac{\left[\frac{A''}{\rho_0 r_{ch_0}^4\left[1+\frac{\alpha}{r_{ch_0}^4}\right]^2} + \frac{B\rho_0}{\left[1+\frac{\alpha}{r_{ch_0}^4}\right]^2} + \frac{C'' r_{ch_0}}{\left[1+\frac{\alpha}{r_{ch_0}^4}\right]}\right] L}{\epsilon_{in}} \right\} \tag{14}$$

where

$$\alpha = 3.10^{-3}\, I_{b_0} I_{ch_0} t^2/\rho_0$$
$$A'' = 6.4 \times 10^{-12}\, I_{b_0} I_{ch_0}^2 t$$
$$C'' = 1.77\, C \epsilon_{in}^{3/2}/(I_{b_0}^{1/2} t^{3/2}).$$

Note the 4th power dependence on r_{ch_0} which comes into various terms and which has been pointed out in the expansion parameter χ previously. In general, it is complicated to see the effects of channel radius on either the energy losses or the transport total efficiency. Solutions to Eq. (14) appear in Fig. 7 for the energy loss efficiency and in Fig. 8 for the transport total efficiency as a function of r_{ch_0} and ρ_0 for the following parameters: I_b = 1 MA, I_{ch} = 50 kA, ϵ_i = 3 MeV, t = 40 nsec, L = 3 m. The effects of the plasma channel radius are now more easily apparent. The energy loss efficiency depends weakly on the channel radius at low channel density as shown in Fig. 7. In general, using small radii causes the plasma to expand so that the final radius does not depend strongly on initial radius. The curves drop as a functions of ρ_0 because of the collisional energy losses.

As for the overall transport efficiency, note in Fig. 8 the *S*-shape of the curves. At small radii, current densities increase and channel expansion can be large leading to small η_J. At large radii, current densities decrease as well as channel expansion and η_{tr} becomes equal to η_ϵ. Increasing the channel radius to more than 1.2 cm at $\rho_0 = 10^{-6}$ g/cc or to more than 0.6 cm at $\rho_0 = 1.6\ 10^{-5}$ g/cc will not bring any significant increase in the value of η_{tr}. At these radii, the decrease in η_{tr} with ρ_0 is due to the decrease in η_ϵ with ρ_0.

Notice that these results are given at $t = 40$ nsec while previous results were given as a function of time.

V. Conclusion

We have shown that in order to minimize electric field losses in a plasma channel where a high intensity light ion beam is injected an optimum density exists for low-Z material and short pulses. We have also shown that no optimum density minimizes reduction in current density associated with the outward convection of the B-field. Finally, we have seen that an optimum density may exist for the overall beam energy flux efficiency.

A practical way of choosing the initial channel density in a channel initially at rest is to ensure that it remains close to ρ_a which is the maximum allowable beam energy degradation, thus providing the highest inertia to beam-induced motion and limiting changes in the initial B-field.

In order to increase the overall beam power density transport efficiency one of the following schemes needs to be considered: channel surrounded by gas blanket, imploding channels and finally channel followed by focusing element. The advantage of this latter scheme is that it can cancel completely in principle the reduction in current density, leaving only energy losses in the channel which depend only weakly on channel radius. For example, the case of $I_b = 1$ MA, $I_{ch} = 50$ kA, $L = 3$ m, $r = 0.56$ cm shows an overall efficiency less than 50% for beam pulses longer than 40 nsec. However, when this same beam current is allowed to propagate in a channel of 1 cm radius for example followed by a focusing element, then the overall efficiency can get as high as 90%.

Acknowledgment

This work was supported by the Department of Energy.

References

1. D.G. Colombant, S.A. Goldstein, and D. Mosher, Phys. Rev. Lett. **45**, 1253 (1980).

2. S.A. Goldstein and D.A. Tidman, Proc. IEEE Int. Conf. on Plasma Science, Madison, Wisc. (1980).

3. S.A. Goldstein, D.P. Bacon, D. Mosher, and G. Cooperstein, Proc. Second Int. Conf. on High Power Electron and Ion Beam Res. and Tech., Ithaca, N.Y. (1977).

4. P.A. Miller, L. Baker, J.R. Freeman, L.P. Mix, J.W. Poukey, and T.P. Wright, ibid.

5. F.L. Sandel, F.C. Young, S.J. Stephanakis, W.F. Oliphant, G. Cooperstein, S.A. Goldstein, and D. Mosher, Bull. Am. Phys. Soc. **25**, 900 (1980); J.N. Olsen, D.J. Johnson, and R.J. Leeper, Appl. Phys. Lett. **36**, 808 (1980).

6. W.M. Manheimer, M. Lampe, and J.P. Boris, Phys. Fluids **16**, 1126 (1973).

7. P.F. Ottinger, S.A. Goldstein and D. Mosher, NRL Memorandum Report 4548 (1981).

8. P.F. Ottinger, S.A. Goldstein, and D. Mosher, Proc. IEEE Int. Conf. on Plasma Science, Madison, Wisc. (1980).

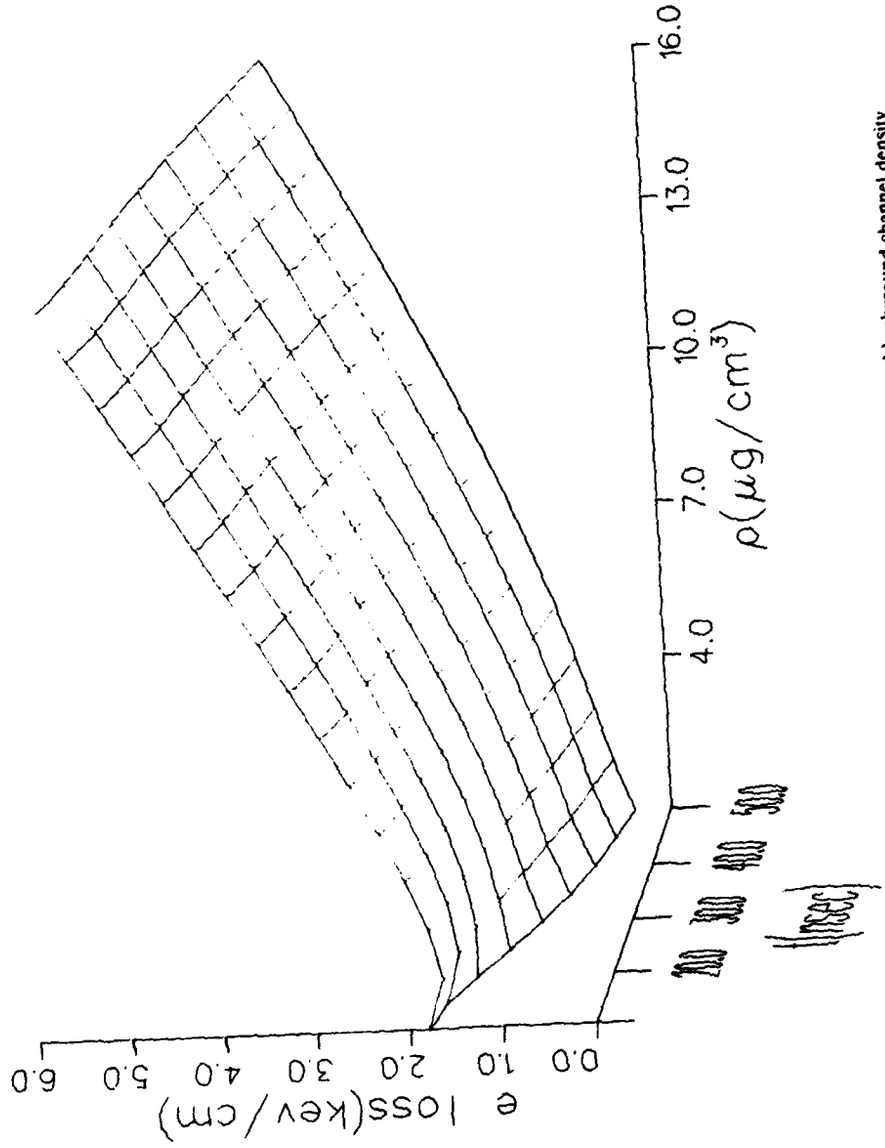


Fig. 1 — Energy losses in keV/cm as a function of beam pulse duration and background channel density for the following parameters $j_{b0} = 1$ MA/cm^2, $I_{ch0} = 50$ kA, $r_{ch0} = 0.56$ cm, and $\epsilon_b = 3$ MeV

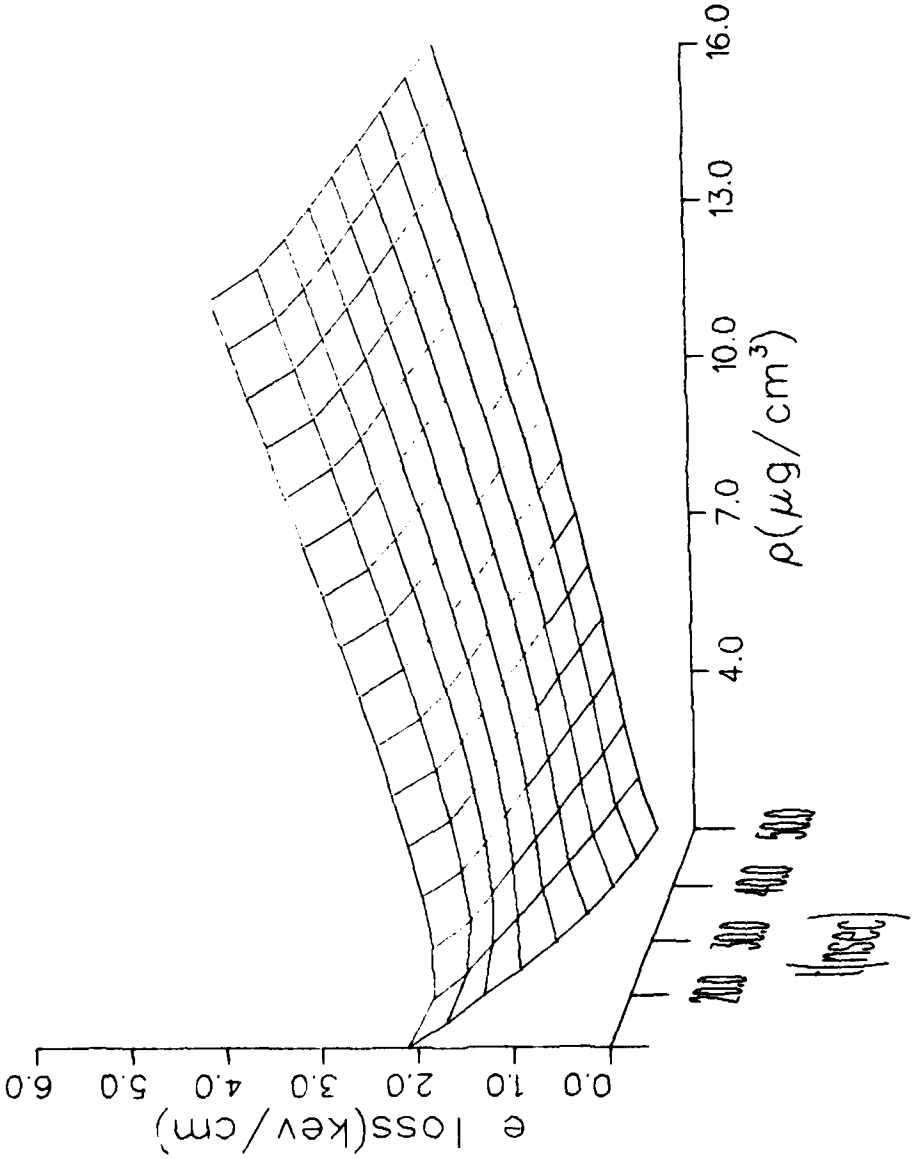


Fig. 2 — Same as in Fig. 1 for ϵ_b = 5 MeV

a) $t = 0$

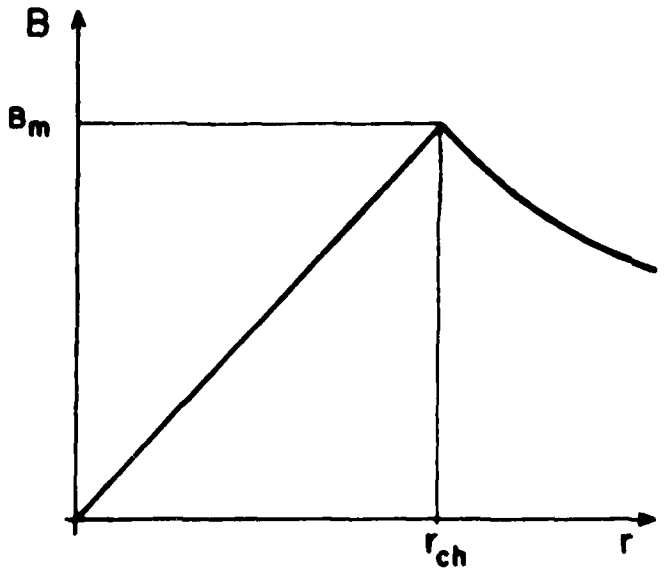
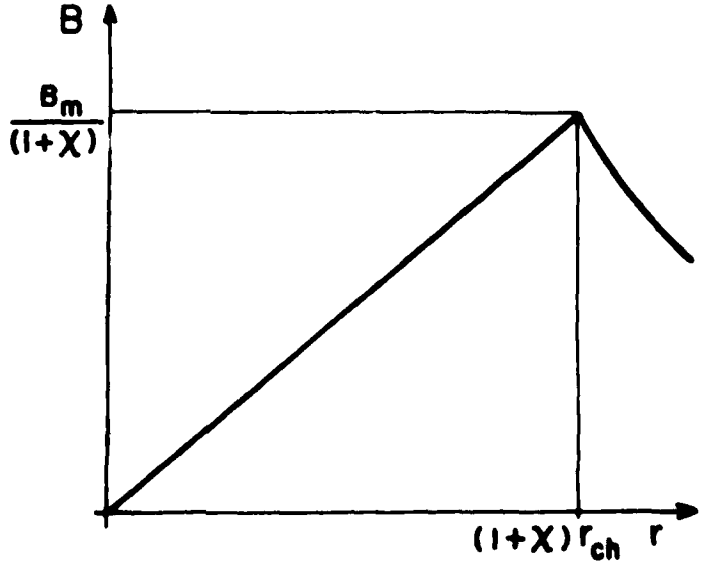


Fig. 3 – (a) Magnetic field configuration in the channel before beam injection (corresponding to uniform channel current density)

b) $t = \tau$



(b) Magnetic field configuration in the channel after beam injection (corresponding to same net current and taking into account channel expansion)

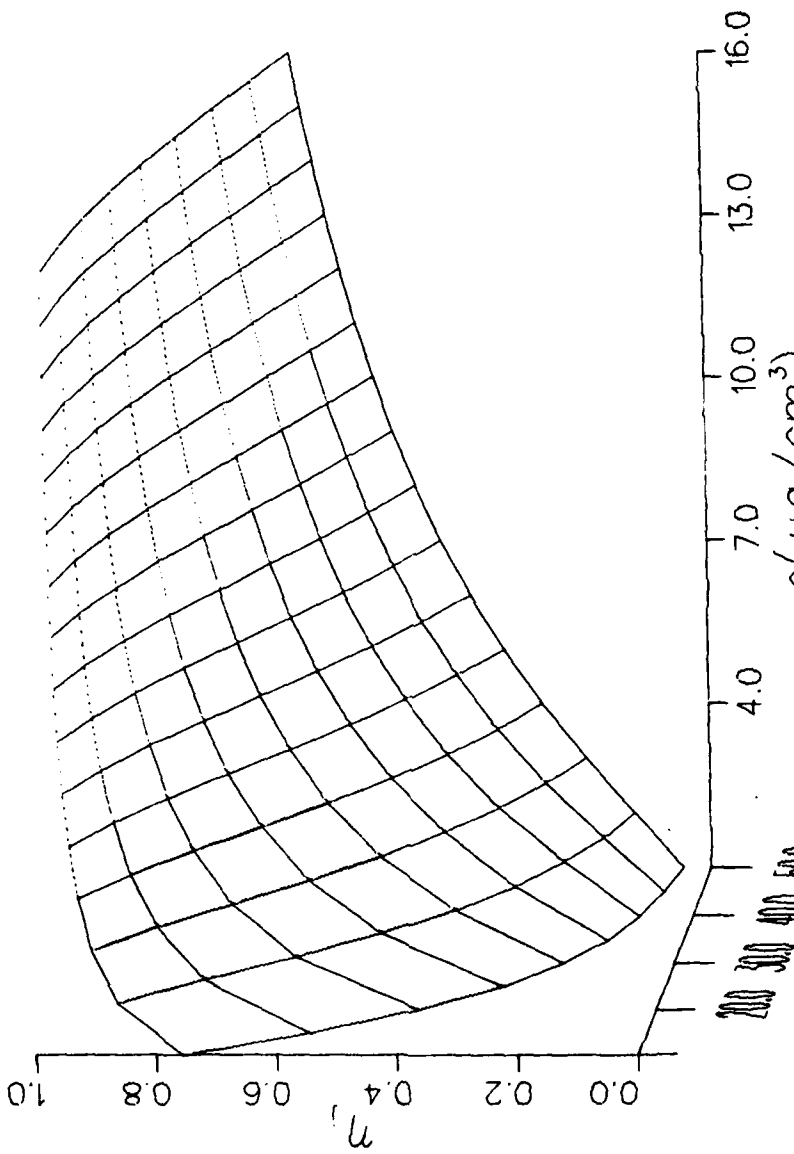


Fig. 4 — Current density reductions as a function of beam pulse duration and background channel density for the same parameters as in Fig. 1 (this curve does not depend on ion beam energy)

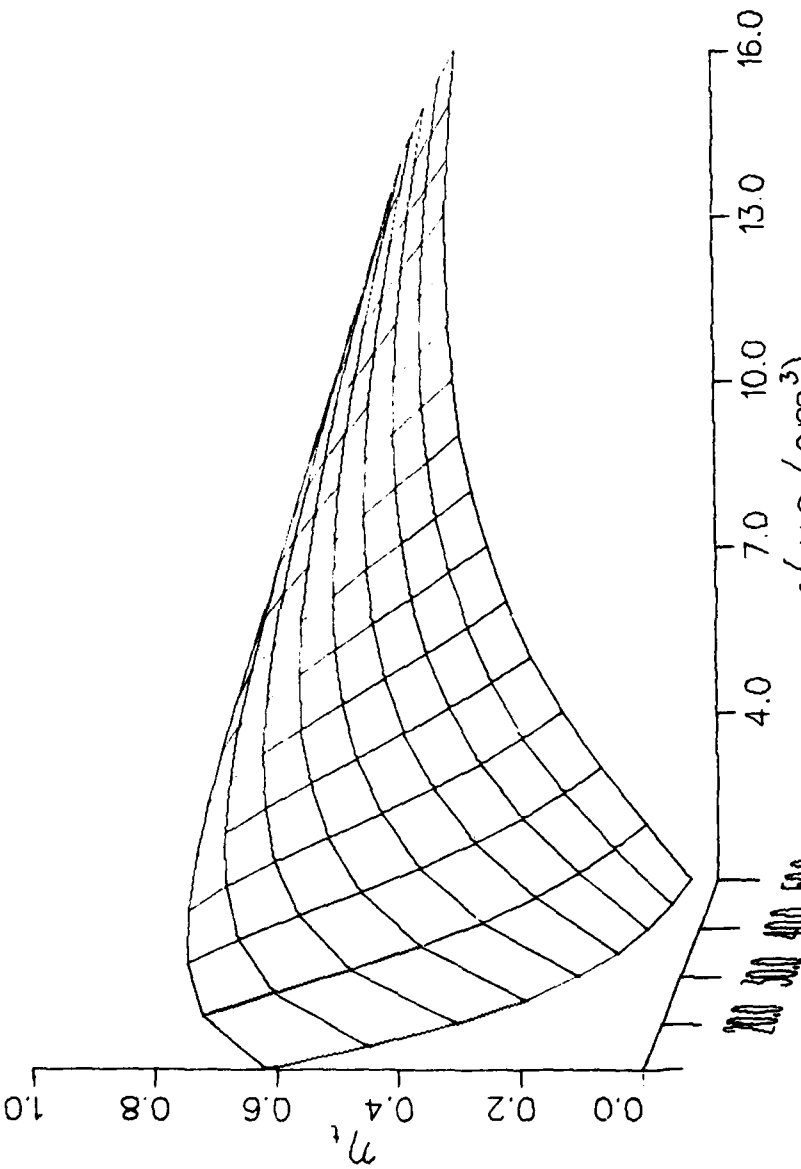


Fig. 5 — Total power density transport efficiency as a function of pulse duration and background channel density for the same parameters as in Fig. 1

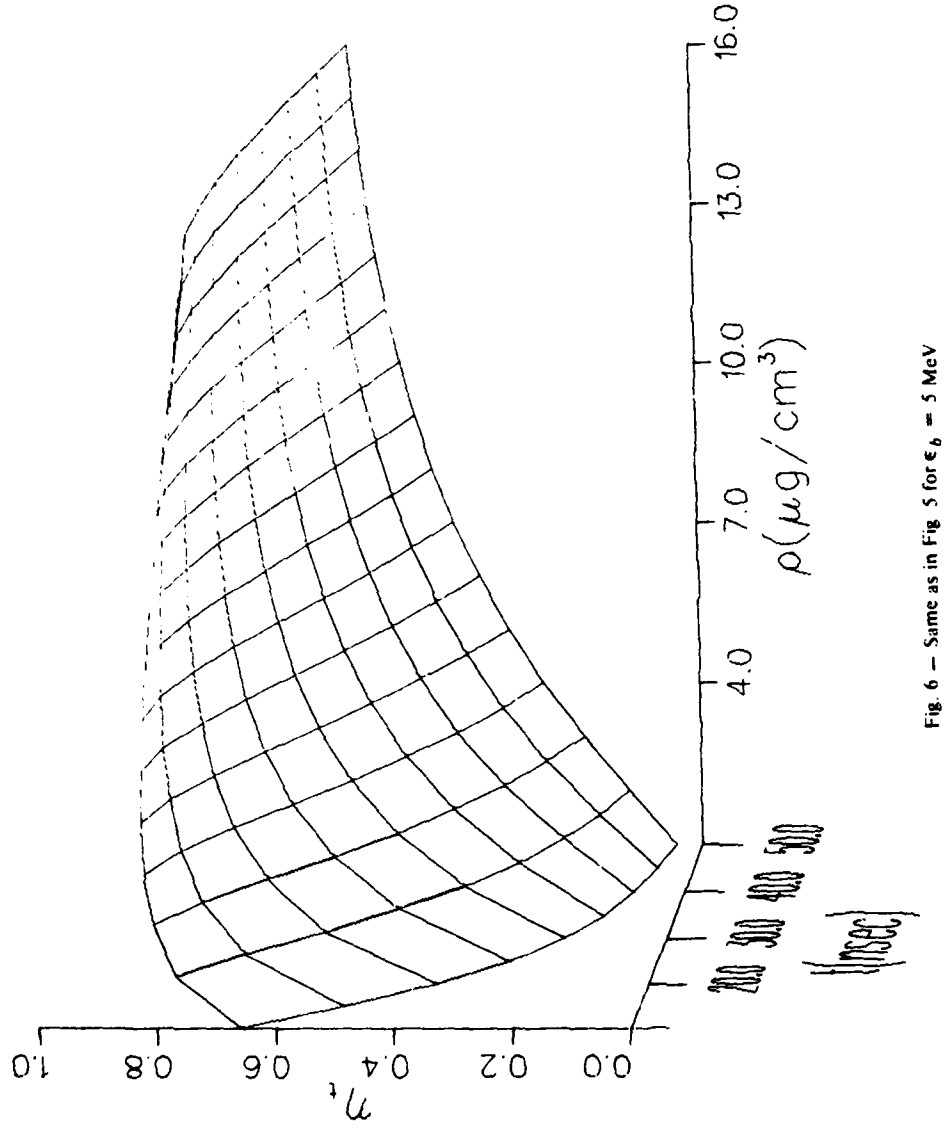


Fig. 6 — Same as in Fig. 5 for ϵ_b = 5 MeV

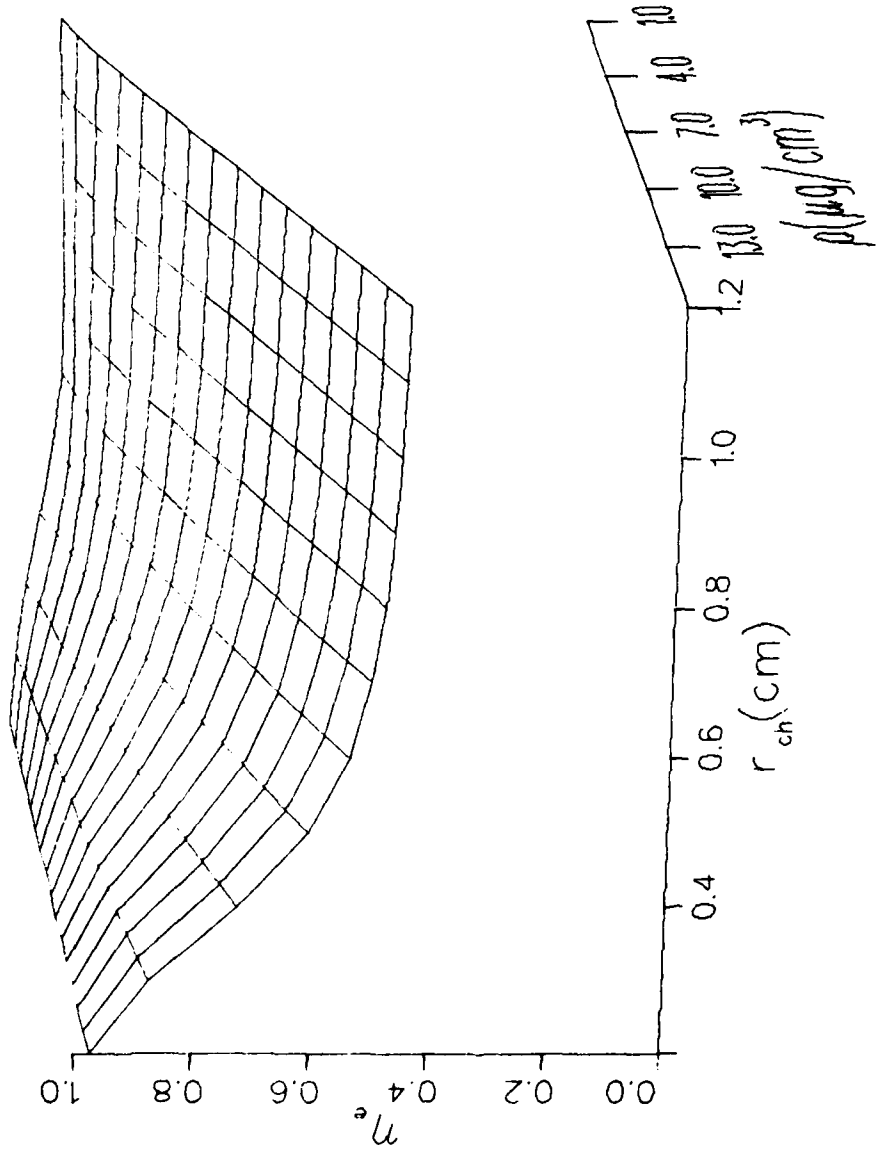


Fig. 7 — Energy transport efficiency as a function of background channel density and plasma channel initial radius for the same parameters as in Fig. 1 at t = 40 nsec

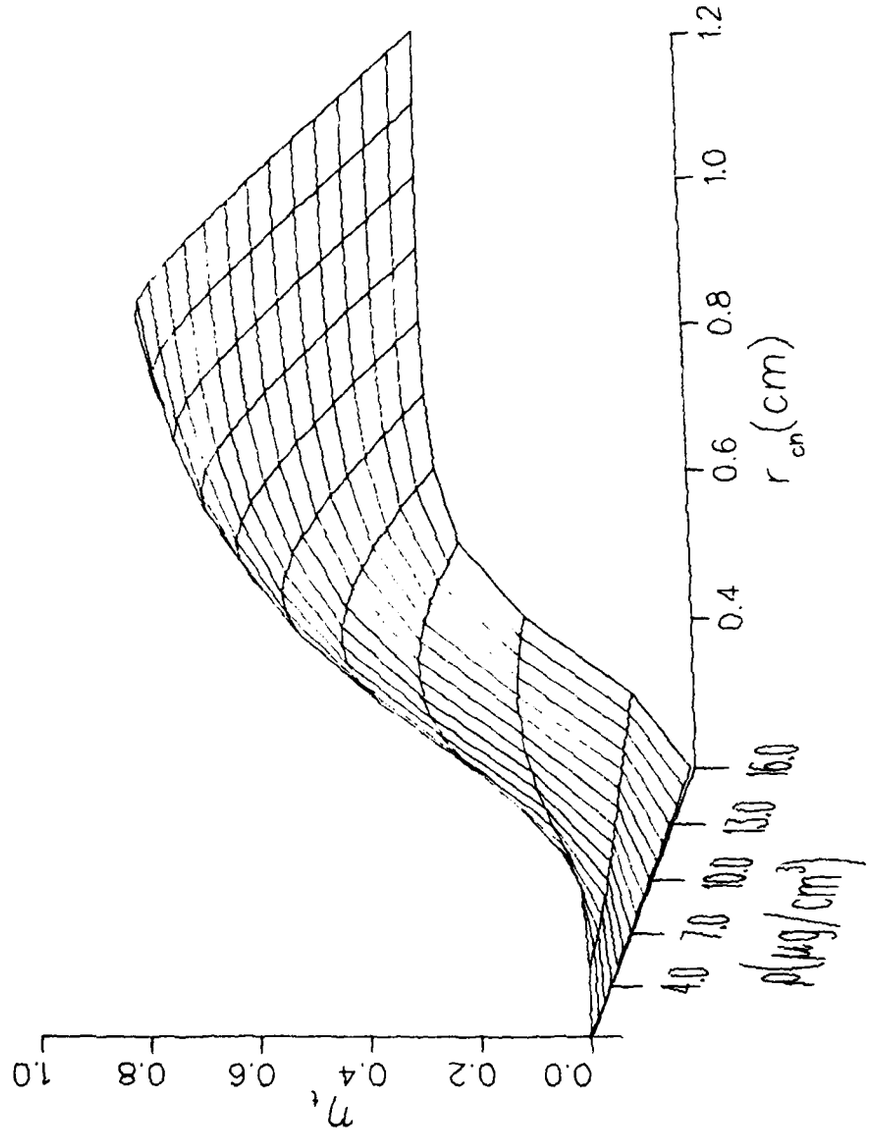


Fig. 8 — Total power density transport efficiency for the case of Fig. 7

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